Sentinel-3A/3B orbit determination using
non-gravitational force modeling and single-receiver ambiguity resolution

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Introduction

Sentinel-3 is an European Space Agency (ESA) Earth observation satellite formation devoted to oceanography and land-vegetation monitoring. Currently two identical Sentinel-3A and -3B satellites are flying at a circular sun-synchronous orbit with an altitude of about 800 km. Their prime onboard payload systems, e.g. radar altimeter, necessitate high-precision orbits, particularly in the radial direction. This can be fulfilled by using the collected measurements from the onboard dual-frequency high-precision multi-channel Global Positioning System (GPS) receivers. The equipped laser retro-reflector allows for an independent validation to the orbits.

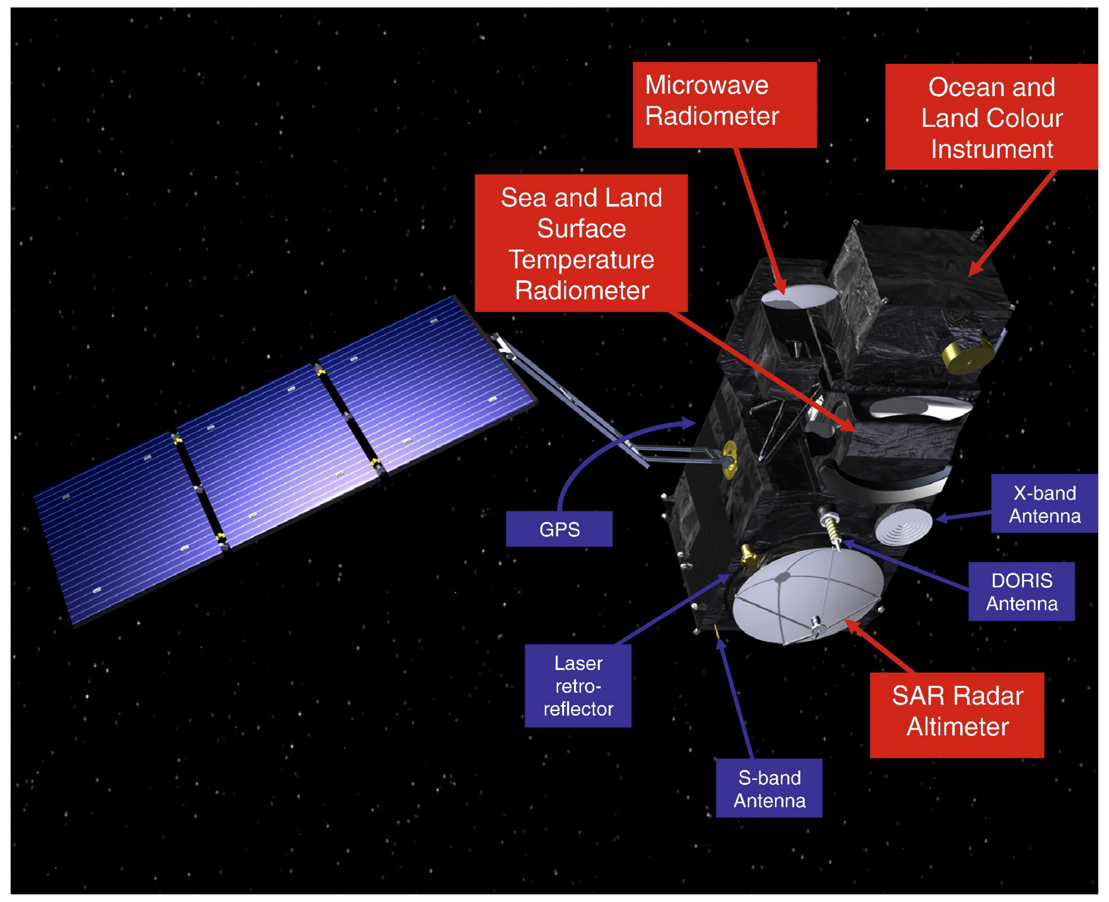

Figure 1: Artist's image of a Sentinel-3 satellite and its prime payloads (credits:ESA).

This research outlines the recent Precise Orbit Determination (POD) methodology developments at the Astronomical Institute of the University of Bern (AIUB) and investigates the POD performances for two Sentinel-3 satellites. Two main implementations are done in our Bernese GNSS software (Bernese): on one hand, use is made of the GNSS Observation-Specific Bias (OSB) products provided by the Center for Orbit Determination in Europe (CODE), allowing for the so-called single-receiver ambiguity resolution (Schaer et al. 2020). on the other hand, a refined satellite non-gravitational force modeling strategy is constructed to reduce the amount of empirical parameters used to compensate the force modeling deficiencies. The latter is the focus of this research.

Orbit Solutions

In Bernese v5.2, a kinematic (*KN*) orbit is described as an epoch-wise trajectory fully independent of any force models, whereas a dynamic orbit is on the contrary. A reduced-dynamic orbit draws a compromise and reduces the strengths of force models using the so-called pseudo-stochastic parameters e.g. the Piecewise Constant Accelerations (PCA) and the once-per-revolution constant accelerations (Jäggi et al. 2006). The equation of motion for this nominal (*NM*) reduced-dynamic orbit can be given by,

$$\ddot{\vec{r}} = -GM\frac{\vec{r}}{r^3} + \vec{f}(t, \vec{r}, \dot{\vec{r}}, Q_1, ..., Q_d, P_1, ..., P_s) \qquad (1)$$

where, $\vec{r}$ is the vector of motion; GM item represents the gravitational forces; $Q_1, ..., Q_d$ indicate d empirical parameters that are set as once-per-revolution constant accelerations in three directions; a total of s PCA (P) are characterized by the a priori statistical properties, e.g. a priori variances σ_p and correlation time τ, which is set as 6 mins in this research. In addition, we introduce a few non-gravitational force models to minimize the heavy dependence on those empirical parameters. The constant accelerations (Q) are completely replaced and the PCA can be more tightly constrained. The new reduced-dynamic orbit is marked as *NG*.

Table 1: Four satellite orbit solutions generated in this research (Note that the PCA settings align in the radial/along-track/cross-track directions).

Solution	Ambiguity	1/revo. acc.	Ngrv	PCA (σ_p, nm/s^2)
FAKN	Float	No	No	No
IAKN	Integer	No	No	No
IANM	Integer	Yes	No	Yes (5.0/5.0/5.0)
IANG	Integer	No	Yes	Yes (0.5/0.5/0.5)

Conventionally, the associated orbit solutions (*KN, NM, NG*) can be computed using the zero-difference GPS observations and the ambiguities remain as float values (*FA*). Since the GPS week 2004 (3/Jun/2018), CODE has been routinely generating the GNSS OSB products, which enable Bernese to generate an integer ambiguity (*IA*) orbit solution (Schaer et al. 2020).

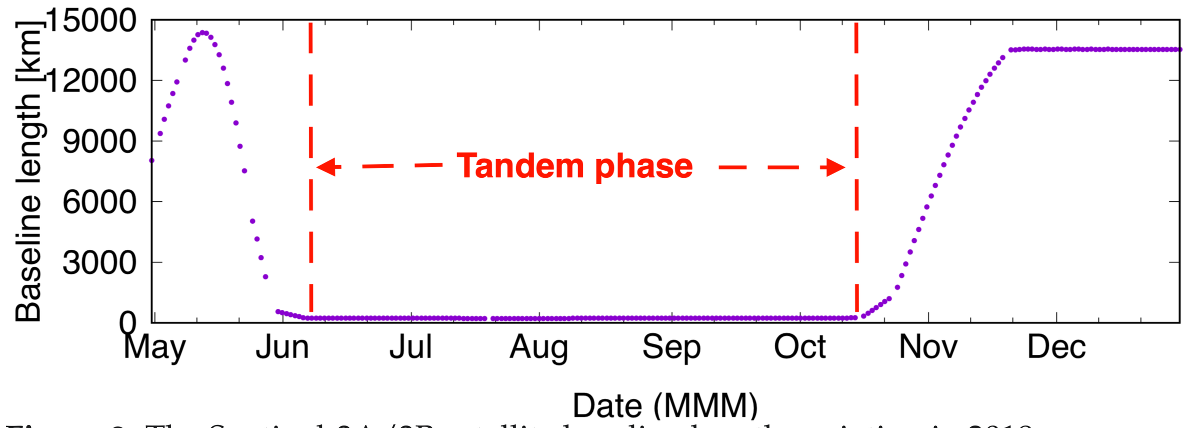

Figure 2: The Sentinel-3A/3B satellite baseline length variation in 2018.

A test period is selected from 7/Jun/2018 to 14/Oct/2018 (Day of Year: 158-287), when two Sentinel-3 satellites operated in a tandem formation maintained at a separation of about 30 s. This foresees nearly identical in-flight environment for both satellites and thereby enables direct POD performance comparisons.

Non-gravitational Force Modeling

The non-gravitational forces profile used in Equation 1 can be given by,

$$\vec{f}_{Ngrv} = S_{SRP}\vec{f}_{SRP} + \vec{f}_{REF} + \vec{f}_{EMT} + S_{AF}\vec{f}_{AF} \qquad (2)$$

where, the Solar Radiation Pressure (SRP), the Earth REFlectivity (REF) and EMissiviTy (EMT) radiation pressure, and the Aerodynamic Force (AF) are surface forces acting on a detailed satellite geometry and its characteristics can be described by a macro-model. This research uses the Sentinel-3 macro-model in (Montenbruck et al. 2018). The two fundamental forces, SRP and AF, are scaled by the estimated scaling factors.

Table 2: Overview of the non-gravitational force modeling (Mao et al. 2020).

Aerodynamic force	Plate-wise lift and drag DTM-2013 atmospheric density model HWM-14 horizontal wind model Goodman accommodation coefficients Scaling factor
Solar radiation pressure	Plate-wise direct pressure Spontaneous thermal re-emission for non-solar panels Conical Earth shadow and solar eclipse Coefficients for optical radiation Scaling factor
Earth radiation pressure	Plate-wise reflectivity and emissivity radiation pressure Spontaneous thermal re-emission for non-solar panels Coefficients for optical and infrared radiation Monthly grids based on CERES-S4 radiosity products Interpolation between neighboring monthly grids

Fig.3 shows SRP is the dominating non-gravitational force for two satellites due to the large solar panels. AF modeling at this fairly high orbit is negligible. The Earth radiation pressure (REF and EMT) mostly projects onto the radial direction and causes a discrepancy of more than 30 nm/s^2 w.r.t the empirical accelerations estimated in the *NM* solution. This suggests orbit shift in the radial direction.

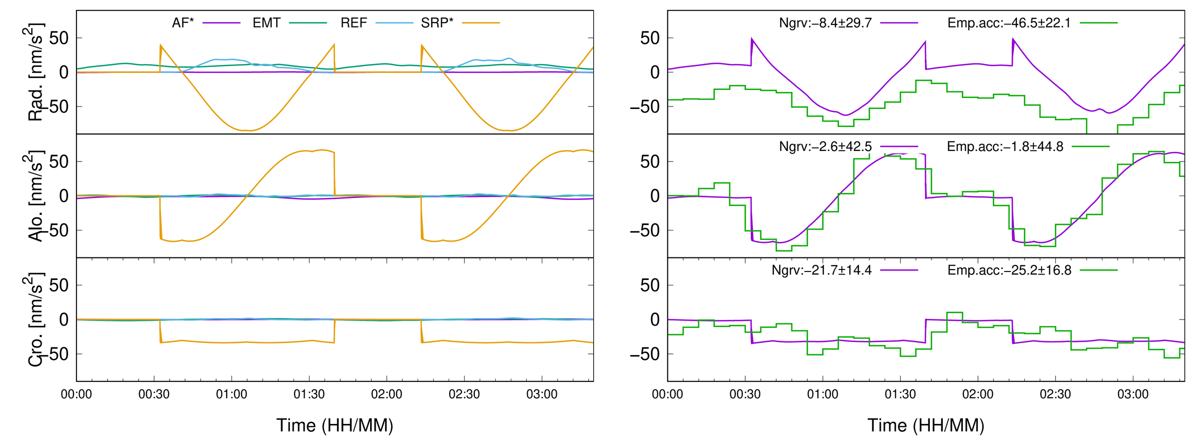

Figure 3: Non-gravitational force modeling for the Sentinel-3A satellite during its first two orbit revolutions on 7/Jun/2018. Left: Each modeled force in the *NG* orbit solution. The SRP and AF are scaled. Right: Comparison between the sum of all modeled forces and the empirical acceleration estimates in the *NM* solution.

Internal Consistency Check

The scaling factor estimates for AF and SRP are depicted in Fig.4, which first indicates an over-performed modeling of AF. This is caused by a high orbit and often atmospheric density models are over-performing during the low solar activity seasons. It is interesting to see that the scaling factors for SRP slightly differ between two satellites. Beside that, the *IANG* orbit solution significantly impacts on the scaling factors by introducing more geometry constraints. This hints for satellite geometry differences, e.g. macro-model characteristics and instrument reference coordinates, between two satellites.

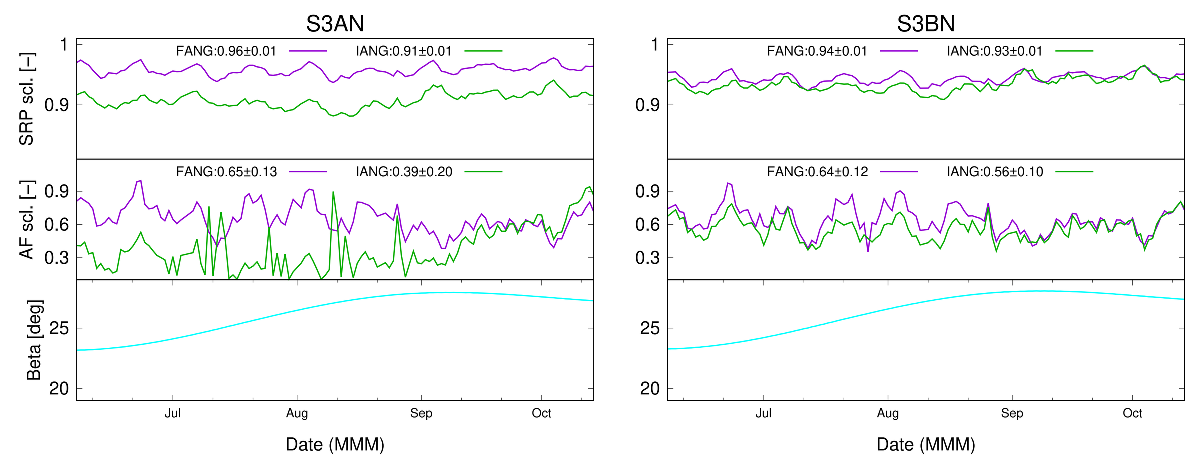

Figure 4: The SRP (top) and AF (middle) scaling factors for the Sentinel-3A (left) and -3B (right) satellites. The satellite beta angle is depicted at bottom.

Fig.5 shows the non-gravitational force modeling strategy clearly shifts satellite orbits in the radial direction. In addition, the integer ambiguity resolution will further constrain the orbit in particularly the cross-track direction, agreeing well with the conclusions in (Montenbruck et al. 2018).

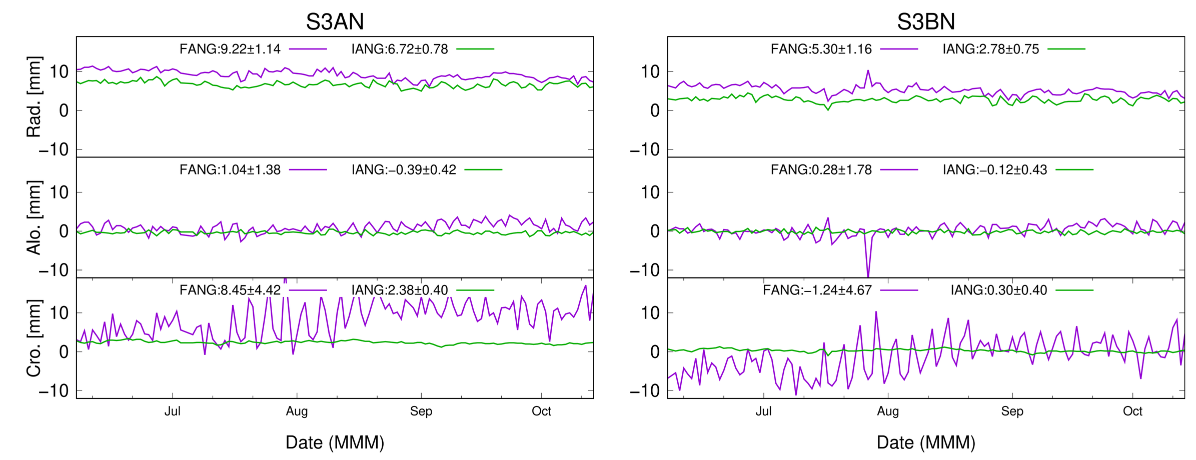

Figure 5: Orbit comparison between the *NG* orbits and their corresponding kinematic orbit for two satellites.

Satellite Laser Ranging Validation

The independent Satellite Laser Ranging (SLR) measurements are used to validate our orbit solutions. Tab.3 and Fig.6 show that the SLR validation residuals decrease significantly after first introducing integer ambiguities, and then the non-gravitational force modeling strategy in POD. The former adds more geometry constraints to the orbit and the latter significantly improves the orbit particularly in the radial direction. The best possible orbit precisions are at levels of sub cm for both satellites.

Table 3: Mean and standard-deviation statistics of SLR residuals in the line-of-sight direction and mean offset in each component direction for the Sentinel-3 satellites using normal points collected by 10 selected stations (elevation cut-off angle: 10 deg, outlier screening: 200 mm), unit: [mm] (Arnold et al. 2019).

Satellite	Orbit	Nr.obs [-]	Mean	STD	Rad.	Alo.	Cro.
S3AN	FAKN	12069	-8.22	17.42	-12.54	-1.36	2.13
	IAKN	12069	-5.49	11.73	-8.20	-2.00	0.67
	IANM	12089	-5.57	10.41	-8.33	-1.93	0.38
	IANG	12089	-0.57	9.97	-0.56	-2.32	2.53
S3BN	FAKN	13194	-5.83	18.55	-8.49	3.80	6.31
	IAKN	13194	-3.71	11.37	-5.55	3.23	2.58
	IANM	13203	-3.62	9.96	-5.34	3.44	2.46
	IANG	13203	-1.08	9.46	-1.48	3.07	2.24

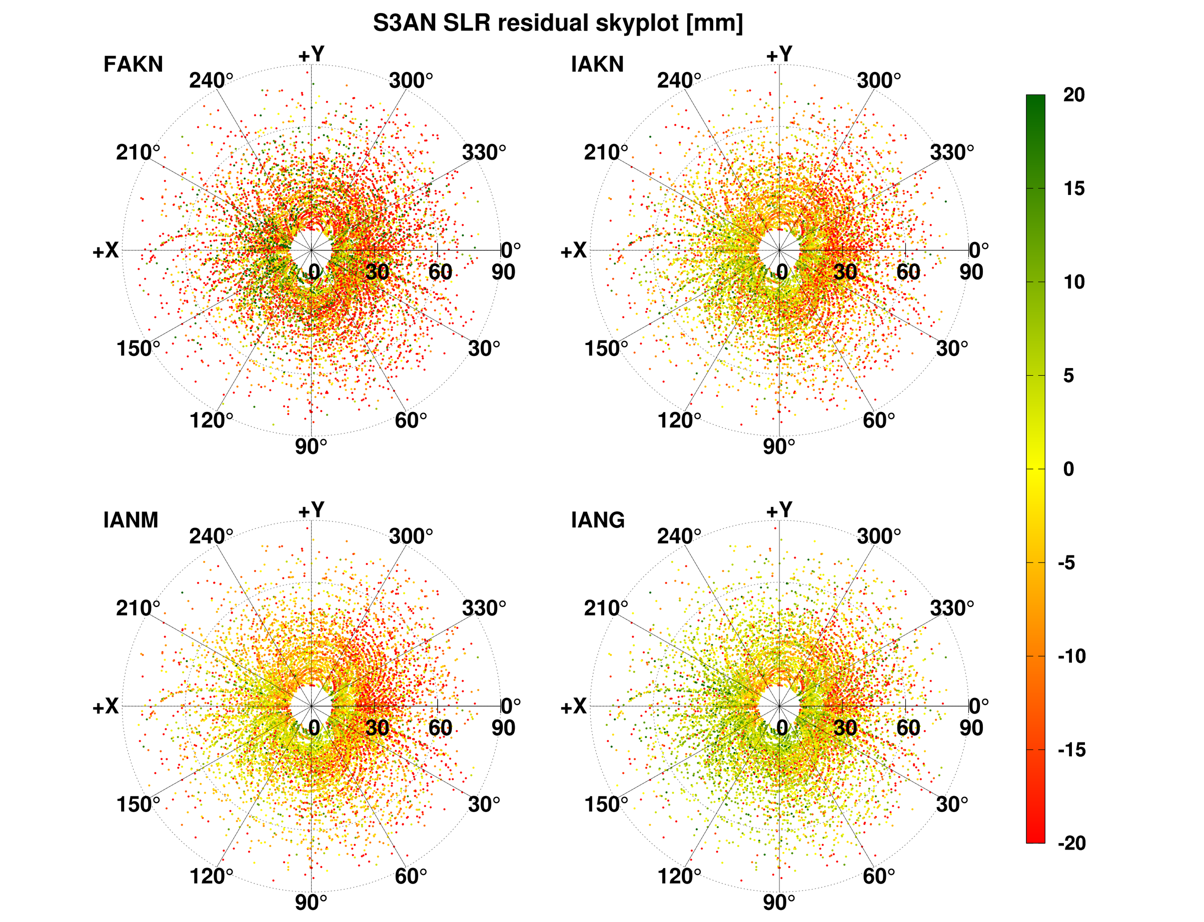

Figure 6: The Sentinel-3A SLR residual distributions on sky-plots.

Conclusions

- The single-receiver ambiguity resolution provides significantly more geometry constraints to the orbit solutions.
- The non-gravitational force modeling orbit solution generates the superior orbit quality. In particular the orbit offset in the radial direction is almost mitigated.
- These LEO POD implementations will be officially released in the coming Bernese GNSS software v5.3.

References

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